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PROSPECTS FOR SPIN PHYSICS AT RHIC*

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ABSTRACT

The proposal to perform polarized proton-proton collisions at collider energies at RHIC is reviewed. After a brief reminder of the desirability of high energy spin physics measurements, we discuss the machine parameters and detector features which are taken to define a program of spin physics at RHIC. Some of the many physics processes which can provide information on polarized parton distributions and the spin-dependence of QCD and the electroweak model at RHIC energies are discussed.

1. Motivation for collider energy spin-physics

The parton structure of the proton, first revealed by deep inelastic scattering (DIS), continues to excite interest as experiments[1] extending that program to lower values of x now probe the QCD structure of the proton in new regimes. In a similar way, polarized DIS experiments have shown that the spin structure of the proton is more complex than envisaged by naive considerations based on the constituent quark model. The EMC[2] measurements of $g_1^{(p)}(x)$ first suggested that the total contribution of the light quarks to the proton spin was surprisingly small ($\Delta\Sigma = \Delta u + \Delta d + \Delta s << 1$) and that there is a non-negligible contribution from sea quarks ($\Delta s \neq 0$). Motivated by these results, new experimental tests designed to accurately measure the spin-dependent structure functions of both the neutron and proton (thereby testing the Bjorken sum rule) were undertaken. The results of the SMC[3] and SLAC[4] experiments have been consistently analyzed[5] and imply that:

- The Bjorken sum rule has been verified to $\sim 10\%$ or, equivalently, the value of $\alpha_S(Q^2 = M_Z^2)$ extracted from the sum rule (including radiative corrections) is consistent with values extracted from many other QCD processes.
- The individual Ellis-Jaffe sum rules for the proton and neutron are best fit with a non-zero value of Δs, indicating a non-zero sea quark polarization.

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- The light quark contribution to the total proton spin, $\Delta\Sigma = \sum_q \Delta q$, which is constrained by the angular momentum sum rule,

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z \rangle \tag{1}$$

  is roughly $\Delta\Sigma = 0.31 \pm 0.07$, indicating that a large fraction of the proton spin arises from polarized gluons or orbital angular momentum.

The lack of flavor separation in polarized DIS[§] and the looser constraint on ΔG imposed by Eqn. 1 as compared with the corresponding sum rule for linear momentum immediately imply that more experimental input to better determine $\Delta G(x)$ and $\Delta\overline{q}(x)$ would be very useful. Many of the most important new constraints on unpolarized parton distributions[7] now come from hadron collisions, so it is natural to study the extent to which a program of high-energy polarized hadron collisions can give information on the spin-dependent parton distributions. Such a program would also provide an opportunity for the systematic study of the spin-dependence of QCD and the electroweak theory for the first time.

Any program of collider-energy spin physics would benefit from the following aspects:

(i) High enough energy to ensure that a leading-twist, perturbative QCD description is unambiguously applicable. Previous polarized *pp* collisions at lower-energy, fixed target facilities have shown dramatic spin effects, but are not obviously reliably describable by perturbative QCD,

(ii) High luminosity is important for any program attempting to measure possibly small asymmetries in cross-sections due to spin-effects,

(iii) Large polarization in both beam and target (so that the fundamental partonic-level hard-scattering spin dependence is not diluted) is valuable. While collisions in which only one hadron is polarized can be used to probe spin-dependence when parity violation is present (as in W/Z production), doubly polarized collisions can make maximal use of the intrinsically large partonic level spin-spin asymmetries ($\hat{a}_{LL}$) in QCD to provide information on the polarized parton distributions. In addition, the possibility of obtaining both longitudinal polarization (which is the type probed by polarized DIS) *and* transverse spin (the effects of which decouple in DIS) is highly desirable,

(iv) If a multi-purpose collider-type detector is not available, the detectors should be versatile enough to still allow for a comprehensive program of spin physics measurements,

[§]Recent measurements of semi-inclusive and inclusive spin asymmetries by the SMC collaboration[6] have, for the first time, allowed for a more direct separation of the valence u and d and non-strange sea quark spin fractions as a function of x.

(v) Finally, one would like such a program to fit naturally and economically into the existing plans and likely funding profiles for high energy physics research.

2. RHIC spin program defined

Building on earlier studies of polarized proton-proton collisions for the then proposed ISABELLE collider[8] and motivated by the first successful tests of the Siberian snake concept[9] (the technology required to maintain proton polarization in circular accelerators), the following parameters[10,11] for a program of polarized pp collisions at RHIC are now thought to be achievable:

- Variable center-of-mass energy in the range $\sqrt{s} = 50 - 500\ GeV$.
- Luminosities up to $\mathcal{L} = 2 \times 10^{32}\ cm^{-2}\,\mathrm{sec}^{-1}$ $(8 \times 10^{31}\ cm^{-2}\,\mathrm{sec}^{-1})$ at $\sqrt{s} = 500\ GeV$ $(50\ GeV)$.
- Both longitudinal and transverse polarization available at the intersection regions of both large detectors with $P^2 \approx (0.7)^2 = 0.5$.
- Rapid switching of the proton polarization can effectively eliminate systematic errors.
- Roughly 10 weeks running time for an integrated luminosity of $800\,(320)\ pb^{-1}$ at $\sqrt{s} = 500\ GeV$ $(50\ GeV)$ per year.

The two large heavy-ion detectors approved for RHIC are STAR (which is a large-acceptance, TPC-based tracking detector) and PHENIX (which emphasizes γ, e, and μ detection). Both detector groups, joined by the RHIC Spin Collaboration (RSC), have put forward a comprehensive proposal[12] to perform a program of collider energy spin-physics measurements which was approved in 1993 as RHIC experiment R5. The STAR detector would be enhanced by an upgrade to include a barrel EMC to aid in jet and direct photon detection. The RIKEN/SPIN group from Japan has promised $20\,M\$$ to provide for the magnets required for obtaining spin (i.e., the Siberian snakes and spin rotators in the RHIC tunnel) as well as for an upgrade[13] of the muon tracking capability of the PHENIX detector which would dramatically enhance it's ability to see Drell-Yan pairs and weak bosons as well as heavy quarks. This additional source of funding, along with the recent successful testing[14] of the partial snake technology in the AGS ring required for injection of polarized protons into RHIC, are, perhaps, the two most important developments in the last year for the continued development of the RHIC spin program.

3. Spin-dependent collider processes

The full use of a hadron collider in which both beams are longitudinally polarized comes from measurements of the spin-spin asymmetry, defined via

$$A_{LL} = P_1 P_2 \left(\frac{\Delta\sigma}{\sigma}\right) = P_1 P_2 \left(\frac{\sigma(++) - \sigma(+-)}{\sigma(++) + \sigma(+-)}\right) \tag{2}$$

where $P_{1,2}$ are the beam polarizations and $\sigma(+,\pm)$ indicates the differential cross-section for any observable quantity for the case where the first beam is polarized in the + direction while the second is in either polarization state. The spin-dependent cross-sections are given by

$$\Delta\sigma \quad \propto \quad \sigma(++) - \sigma(+-) = \sum_{i,j} \int\int \Delta f_i(x_1)\, \Delta f_j(x_2)\, \hat{a}_{LL}^{(i,j)}\, d\hat{\sigma}_{i,j} \tag{3}$$

where $\Delta f_{i,j}(x)$ are the polarized parton densities and the partonic-level spin-spin asymmetry is defined by

$$\hat{a}_{LL}^{(i,j)} = \frac{d\hat{\sigma}_{i,j}(++) - d\hat{\sigma}_{i,j}(+-)}{d\hat{\sigma}_{i,j}(++) + d\hat{\sigma}_{i,j}(+-)} \tag{4}$$

for each contributing subprocess. Many of the $\hat{a}_{LL}$ for subprocesses contributing to familiar QCD processes (such as direct γ, jet, and Drell-Yan production are as large as possible, close to $|\hat{a}_{LL}| \approx 0.8-1$) Experimental measurements of A_{LL} thus give information on the spin-dependent parton distributions as well as the intrinsic spin-dependence. Single spin asymmetries, defined as

$$A_L = P_1 \left(\frac{\sigma(+) - \sigma(-)}{\sigma(+) + \sigma(-)}\right) \tag{5}$$

are also possible if there is intrinsic parity violation in the process, as in weak boson production. The intrinsic spin-dependence and sensitivity to polarized parton distributions for many standard model processes have been studied in the context of the RHIC spin program and we give some examples below.

3.1. Direct γ production

Given the important role that direct photon production has played in the determination of the unpolarized gluon distribution, it is not surprising that it is touted[15] as an effective tool for probing $\Delta G(x)$. At leading order, the Compton diagram $qg \to q\gamma$ dominates (especially in pp collisions) and measurements of the asymmetry in the γ plus away-side-jet cross-section provide an almost direct measure of $\Delta G(x)/G(x)$. Even without such identification, strong constraints on the magnitude of $\Delta G(x)$ can be obtained. The next-to-leading-order (NLO) corrections have been performed by two groups[16] who find that the LO predictions for the spin-spin asymmetry are perturbatively stable.

3.2. Jet production

The number of subprocesses contributing to jet production[17] is larger, with the relative importance of individual QCD subprocesses (gg, qg, and qq initial states) varying with p_T or M_{jj}. The observation of A_{LL} at large p_T, where the qq subprocesses dominate and where the polarization of the valence quarks is known to be large, should provide a benchmark test of the QCD predictions for collider spin physics. The partonic-level asymmetries for all of the leading-order QCD processes are large[18] as well as those

for the $2 \to 3$ processes[19] which could contribute at NLO. While the NLO corrections to jet production in polarized hadron collisions have not yet been completed, the necessary NLO helicity-dependent $2 \to 2$ matrix-elements have been calculated.[20]

3.3. Heavy quark production

Armed with the NLO corrections to heavy quark production, it has been suggested[21] that b-quark production can be used to provide constraints on the unpolarized gluon densities in the proton. Early discussions of heavy quark production in polarized pp collisions, which focused on spin asymmetries in the total cross-section[22] , have been extended[23] to include the p_T dependence which was found to be dramatic, leading to a maximally large value of $\hat{a}_{LL} = -1$ for $p_T >> M_Q$. It has been suggested[23] , however, that NLO corrections could change the LO picture. Recent NLO calculations of $Q\overline{Q}$ production in polarized $\gamma\gamma$ collisions[24] tend to support this conjecture where the dominant $(+-)$ helicity combination is perturbatively stable while the highly suppressed (at leading order) $(++)$ contribution receives a very large NLO correction. The enhanced PHENIX capability for b-quark detection makes further study of this process highly desirable. It could well provide an interesting test of the subtle interplay of LO and NLO spin-dependence in QCD.

3.4. Other processes probing $\Delta G(x)$

There have been a number of studies of other processes which are sensitive to $\Delta G(x)$, namely 3-jet[19] and 4-jet[25] production, ψ production at both low[26,22,27] and high[28] p_T, double-photon production[29] , and $\psi + \gamma$ production.[30]

3.5. Probing $\Delta\overline{q}(x)$

The Drell-Yan process is the standard hadronic probe of the anti-quark distribution and many studies of its role in polarized pp collisions, both in the context of γ^*[31,32] and W/Z[33,34] production have appeared. Such studies are timely as RHIC may be the best laboratory for the study of the $SU(2)$ structure of the polarized and unpolarized[35] sea quark distributions.

3.6. Measuring transversity distributions

The other leading twist-2 observable corresponding to the distribution of transverse spin in a proton[36] decouples from DIS because of a helicity mismatch. No experimental information is currently available on its magnitude, although bag model studies suggest that it is of the same order as the corresponding longitudinal quantity. The 'transversity' distribution gives a leading-twist transverse spin asymmetry (A_{TT}) in polarized Drell-Yan production, but in pp collisions it probes a combination of unknown quark *and* anti-quark 'transversities'; further information to help separate the two may come from transversely polarized Z production.[33] Jet production at large p_T, where qq scattering dominates, can show a non-vanishing A_{TT} depending on the valence quarks alone; the corresponding partonic-level spin-spin asymmetries, $\hat{a}_{TT}$, are,

however, smaller than the corresponding $\hat{a}_{LL}$ for both 2-jet[37] and 3-jet[38] production due to a color mismatch in the required interference diagrams. High statistics experiments will likely be needed[39] to study the signal in the region where the transversity distribution is important in this sector.

4. Summary

A polarized proton-proton facility at RHIC will be a unique laboratory for the measurement of the longitudinal and transverse spin-dependent parton distributions and for testing the spin-dependence of QCD and the electroweak interactions. It is a more versatile program for measuring $\Delta G(x)$ than other more specialized proposals and is nicely complementary to the RHIC program of heavy ion physics; hadron spin-dependence and structure function physics are now sometimes considered as one of the 'new' directions in nuclear physics and share important non-perturbative physics aspects with the deconfinement transition expected as the ultimate goal in the quest for the quark-gluon plasma. The addition of a spin physics program to the RHIC project provides a large physics benefit at a small incremental cost.

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